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PREDICTED EFFECTS OF TRANSIENT BURNING ON GUN FLAMESPREADING

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April 1978

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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NOVA code calculations were performed to predict flamespreading and pressure waves in an Army 155mm howitzer full bore charge (155) and the Navy 5 inch, 54 caliber gun (5/54) with a special service charge. A Zeldovich form of a transient burning model replaced the usual quasi-steady pressure dependence of regression rate. Some differences were noted for the Army application; Navy calculations showed a wide difference. Both calculations showed that transient burning can affect an interior ballistics calculation although several refinements are needed before full gun calculations can be performed.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Arrhenius pre-exponential
E	Arrhenius activation energy
h	convective heat transfer coefficient
h_c	nominal heat transfer coefficient
P	pressure
Q	heat flux to propellant
R	universal gas constant
r	regression rate
r_s	quasi-steady regression rate
T	temperature
T_{abl}	gasification temperature
T_s	surface temperature
Z	distance into solid
x	axial distance in bed
α	thermal diffusivity
τ	transition time [Eq. (5)]
ϕ	temperature gradient at burning surface
τ	thermal conductivity of propellant
σ_p	temperature sensitivity of regression rates

Subscripts

ign	at propellant ignition
c	convection
o	initial condition

I. INTRODUCTION

Most transient, one-dimensional, interior ballistic calculations have assumed that, once ignited, the propellant regression rate is given by a quasi-steady power law dependence on pressure. Increasing the low pressure rate by adding an arbitrary constant (of the same order as the quasi-steady rate) has occasionally improved the agreement between predicted and observed pressure waves in guns[1,2]. Such low pressure enhancement is typical of the transient burning rates which have been predicted to exceed the quasi-steady rate by several multiples[3] for a KTSS type model and by about one multiple[4] for the Zeldovich model. This paper will report use of the Zeldovich transient burning model in the NOVA flamespreading computer model applied to a 155mm howitzer and to a five inch gun to predict an effect on the ignition and combustion of a granular bed.

The Zeldovich approach assumes a quasi-steady gas phase in which the transient heat feedback to the propellant surface can be computed from steady state burning rate data. The pressure field in the propellant bed is coupled to the transient heat conduction equation in the burning solid to obtain the instantaneous regression rate. Kooker and Nelson[3] demonstrated that invariant imbedding can be used to solve this type combustion model. Gough[5] provided the two-phase flow model for the gas properties. Coupling the two requires simultaneously solving for the gas pressure and the regression rate of the solid.

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1. *E. B. Fisher and A. P. Trippe, "Application of a Flame Spread Model to Design Problems in the 155mm Propelling Charge", Proceedings of the 12th JANNAF Combustion Meeting, Newport, RI, August 1975.*

2. *A. W. Horst, C. W. Nelson, and I. W. May, "Flame Spreading in Granular Propellant Beds: A Diagnostic Comparison of Theory to Experiment", AIAA Paper 77-856, 13th AIAA Propulsion Specialists Meeting, Orlando, FL, July 1977.*

3. *D. E. Kooker and C. W. Nelson, "Numerical Solution of Three Solid Propellant Combustion Models During a Gun Pressure Transient", Proceedings of the 12th JANNAF Combustion Meeting, Newport, RI, August 1975.*

4. *L. H. Caveny, M. Summerfield, and C. W. Nelson, "Ignition Transients and Pressurization in Closed Chambers", Proceedings of the 11th JANNAF Combustion Meeting, Pasadena, CA, September 1974.*

5. *P. S. Gough, "A Quasi-One-Dimensional Two Phase Flow Model of Interior Ballistics: Towards a Universal Gun Code", Proceedings of the 13th JANNAF Combustion Meeting, Monterey, CA, September 1976.*

II. THEORY

The governing equations and numerical approach for the hydrodynamics of the flow have been described earlier[5,6]. Of interest here is the coupling of the transient combustion with the flow.

In the flow field is distributed a set of marker particles, fewer in number than grid points, convected by the propellant grain velocity. These marker particles are used to compute the transient heating to ignition and mass generation by combustion within the bed. A two-way interpolation operates the continual shuttling between markers and grid points. Conditions at the flow mesh are interpolated to compute a heat flux to the marker particle. Once the surface temperature of the particle has been calculated, the temperatures in the flow field are interpolated for the points between bounding marker particles. Consider a flow mesh with points at x_1, x_2, x_3, x_4, and marker particles at x_a and x_b as shown

o	o	o	o	o	o
x_1	x_a	x_2	x_3	x_b	x_4

with heat flux Q_1, Q_2, and Q_3 computed from flow conditions. Then by interpolation

$$Q_a = Q_1 + (Q_2 - Q_1)\left(\frac{x_a - x_1}{x_2 - x_1}\right) \tag{1}$$

The temperature field in the particle is then computed by solving the transient heat conduction equation to obtain surface temperatures T_a and T_b. T_2 is then obtained again by interpolation

$$T_2 = T_a + (T_b - T_a)\left(\frac{x_2 - x_a}{x_b - x_a}\right) \tag{2}$$

Once ignition of a bounding particle (x_1 or x_2) occurs, the procedure should recognize the shift from a simple convective heat transfer. The flux Q_1 is computed as though the solid were still being convectively heated but the heat is <u>not</u> taken from the gas phase energy equation. This process continues until the entire solid phase is ignited. Inaccuracies admitted by this procedure are accepted to avoid the computational expense of tracking the temperature field in the entire solid phase region. Typically eight marker particles were used in a grid mesh of 35 points.

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6. *P. S. Gough, "Numerical Analysis of a Two-Phase Flow with Explicit Internal Boundaries", Paul Gough Associates Report PGA-TR-76-2, September 1976 (See also NOS Indian Head Report IHCR 77-5, April 1977).*

Before ignition, the solution to the transient heat conduction equation is straightforward, given the flux to the heated surface. After ignition, it is considerably more difficult because the non-linear equation has a coupled non-linear boundary condition. For the Zeldovich transient model (4), the surface gradient is given by

$$\frac{\partial T}{\partial Z} = \frac{r}{\alpha}\left[T_s - \frac{1}{\sigma_p}\ln\left(\frac{r}{r_s}\right) - T_o\right] \tag{3}$$

The iterative procedure assumes a trial value for the regression rate to solve for the surface temperature T_s by an invariant imbedding integration (also iterative) of the heat conduction equation. The computed value of T_s is then used in a global burning rate expression

$$r = A\exp[-E/RT_s] \tag{4}$$

Successive values of r are computed until two agree within a specified difference.

Values for r_s in Eq. (3) are obtained by applying the quasi-steady power law (ap^n) to the linearly interpolated pressure at x_a.

This assumption of a sudden transition at the ignition temperature to self-sustaining combustion contradicts observed propellant ignition which shows a developing flame requiring some continued external stimulus after first flame appearance[7,8]. Sustained burning was observed to be preceded by a brief flux-dependent transient flame followed by radiation assisted burning.

There is little direct evidence to validate a quantitative transition model with convective heating fluxes. Qualitative arguments, which can offer mechanisms for the transition flux, yield no numerical values needed for a calculation. NOVA's combination of radiation and forced convection necessitates some arbitrary decisions on heat feedback during the transition.

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7. *T. J. Ohlemiller, L. H. Caveny, L. DeLuca, and M. Summerfield, "Dynamic Effects on Ignitability Limits of Solid Propellants Subjected to Radiative Heating", Fourteenth Symposium (International) on Combustion, The Combustion Institute, pp. 1297-1307, (1973).*

8. *L. DeLuca, T. J. Ohlemiller, L. H. Caveny, and M. Summerfield, "Radiative Ignition of Double Base Propellants: II Pre-Ignition Events and Source Effects", AIAAJ, 14 (8), p. 1111-1117 (1976).*

Andersen[9] suggests one criterion for the time to self-sustaining combustion as

$$\tau = \alpha / r_s^{\,2} \quad . \tag{5}$$

Using this criterion requires a value of r_s in a transient pressure field. Estimates of the local pressurization rate, dP/dt, can be used to extrapolate the pressure. Eq. (5) can then be expressed as

$$\tau = \alpha / \{a[P_{ign} + \int_{t_{ign}}^{\tau} \frac{dP}{dt}\, dt]\}^{2} \tag{6}$$

After a trial and error solution yields the transition time, a mostly arbitrary decrease in convective flux augments the flame heat feedback. One approximation is a linear decrease in time from the flux at ignition (Q_{ign}) such that

$$Q_c = Q_{ign} \quad (t < t_{ign} + \tau) \quad . \tag{7}$$

Total heat flux to the surface is then

$$Q = \lambda\phi + Q_c \quad . \tag{8}$$

After the transition time τ has expired, heat is supplied only by the Zeldovich flame.

Kuo[10] postulated that the gas-to-particle heat transfer coefficient decreased linearly with surface temperature,

$$h = h_o \left[\frac{T_{ign} - T_s}{T_{ign} - T_{abl}}\right] \quad . \tag{9}$$

He reported a typical transition time of about 1μs, which is far smaller than Andersen's criterion and than DeLuca's[8] observation of milliseconds.

There seems little immediate prospect of obtaining a definite estimate of the actual heat transfer from the developing flame. Kooker[11] promises an eventual calculation once the kinetics can be identified.

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9. *W. H. Andersen, "Model of Transient Ignition to Self-Sustaining Combustion", Comb. Sci. and Tech., 5, p. 75, 1972.*

10. *K. K. Kuo, R. Vichnevetsky and M. Summerfield, "Theory of Flame Front Propagation in Porous Propellant Charges under Confinement", Princeton Univ. AMSE Report 1000, August 1971 (AD #762063).*

11. *D. E. Kooker, "Numerical Predictions of Ignition and Flamespreading in Ozone/Oxygen Mixture", Proceedings of the 14th JANNAF Combustion Meeting, Colorado Springs, CO, August 1977.*

As will be seen in the results, the Zeldovich heat feedback by itself is not enough to sustain combustion at low pressures.

In a typical heating to ignition, the heating rate rises from zero to 640 $J/cm^2/sec$ in about 0.5ms. The average rate of 430 $J/cm^2/sec$ is too high to compare directly with DeLuca's experimental results. At DeLuca's highest rate (80 $cal/cm^2/sec$) the delay time between faint and strong IR signal (Fig. 3a, Ref. 8) was 0.5ms at 21atm to 2ms at 5atm. At the pressures calculated by NOVA where ignition occurs at about 30atm, the transition times should be less than 1 ms to a self-sustaining combustion.

Earlier studies by Caveny et al[4] noted the transition problem. Heating was imposed at 840 $J/cm^2/sec$ with a linear decay to zero in 0.5 or 1.0ms after ignition which occurred at 0.5MPa. To insure a continued flame, heat from a forced convection to the surface was added whenever Zeldovich stability parameters indicated unstable burning. Relative burning rate peaked at a pressure of 3.3MPa.

Given the unavailability of a full solution and the arbitrary previous approaches, it is not unreasonable to adopt the Andersen criterion with a linear ramp as given by Eq. (7).

A linear interpolation of relative burning rate (r/r_s) converts the marker particle transient rates to the grid mesh rates

$$r_2 = r_{s_2}\{(\frac{r}{r_s})_a + [(\frac{r}{r_s})_b - (\frac{r}{r_s})_a][\frac{x_2 - x_a}{x_b - x_a}]\} . \tag{10}$$

Again a judgment is made that relative burning rate is a more useful variable to interpolate than absolute rate. When the interpolation region includes a steep pressure gradient, neither absolute nor relative rates should be expected to vary linearly with distance. Although it is not yet clear which is closer to linearity, intuition says that interpolating the relative rate will cause a smaller error. A sensitivity test must precede any definitive judgment.

III. UNCOUPLED PROBLEM

To lower computer costs while investigating the transient burning response to the expected gun conditions, the NOVA transient burning subroutines were extracted and run with imposed typical pressure and heat flux histories. Parametric studies then established the sensitivity of the predicted transient burning rate response to variations in the gun conditions and input data. For the 155 with nominal input data, the heat flux computed in Ref. 12 and pressure at the marker particle nearest the breech could be approximated as

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12. *C. W. Nelson, "Comparison of Predictions of Three Two-Phase Flow Codes", 13th JANNAF Combustion Mtg, Monterey, CA, September 1976.*

$$\frac{dQ}{dt} = 3.7 \times 10^7 \frac{J}{sec^2 cm^2} \qquad (t < t_{ign}) \qquad (11)$$

$$\frac{dP}{dt} = 7000 \frac{MPa}{sec} \quad . \qquad (12)$$

After ignition, heat flux is computed by Eq. (7) and Eq. (8).

Surprise! The propellant flame cannot sustain itself. Heat feedback from the Zeldovich formulation is not enough to maintain the combustion unless supplemented by an assumed source outside the flame. The delay time of 0.5ms computed from Andersen's criterion must be arbitrarily longer. A series of trials showed that about 2ms was enough to allow a transition to stable behavior in this problem. Successful transition is the correct criterion because the gun charge does ignite and burn. Such pathological examples as stuttering or delayed ignition were not intended to be handled with this code and will be left for another study.

Sensitivity studies were performed with the uncoupled version to find the combustion guidelines for the full gun cases. With the 155 propellant properties of Table II some of the results are shown in Table I.

Table I. Sensitivity Studies, Uncoupled Problem

Case	Transition Time (ms)	$\sigma_p (°R)^{-1}$	$\max(\frac{r}{r_s})$	Remarks
1	2.5	0.004	4.0	
2	6.0	0.003	3.1	
3	1.0	0.003	2.9	
4	0.5	0.003	1.5	Flameout
5	2.0	0.002	2.2	
6	0.5	0.002	1.3	Flameout
7[a]	6.0	0.004	4.0	Flameout
8	6.0	0.003	2.9	E_s 17 kcal/mol
9	2.0	0.0025	2.4	

Note a - Regression rate convergence 0.1 percent.

It is discomforting to discover a go-no go sensitivity to such an arbitrary parameter as the details of an indeterminable heat flux. Because the combustion details are secondary to the hydrodynamics of the flow in a burning propellant bed, the transition parameter must be set to avoid extinguishment. The price to be paid is a higher peak relative burning rate and a greater mass generation in the transient period.

IV. GUN CALCULATIONS

With the transient burning coupled to the hydrodynamics, NOVA was used to calculate the performance of two guns for which tests data are available for comparison. Earlier reports have described attempts to simulate the gun performance by quasi-steady burning rates modified (in some cases) to obtain agreement with test data. Input data for the two guns are shown in Tables II and III.

Table II. Input Data

	155mm Howitzer	5/54 Gun
Initial Temperature	294 K	306 K
Propellant Density	1.58 g/cm^3	1.55 g/cm^3
Propellant Charge	9.9 kg	9.4 kg
Grain Shape	7 perf cylinder	7 perf cylinder
Outer Diameter	10.67 mm	10.0 mm
Perforation Diameter	0.86 mm	1.0 mm
Grain Length	24.3 mm	23.4 mm
Chemical Energy of Propellant	4420 J/g	3900 J/g
Gas Molecular Weight	23.46	22.89
Specific Heat Ratio	1.24	1.246
Co-volume	.944 cm^3/g	.933 cm^3/g
Igniter Chemical Energy	3980 J/g	1568 J/g
Igniter Molecular Weight	23.0	36.1
Igniter Specific Heat Ratio	1.245	1.25
Tube Diameter at Breech	185 mm	142 mm
Tube Radius at Bore	155 mm	127 mm
Projectile Mass	43.1 kg	24.1 kg
Settling Porosity of Bed	0.53	0.50
Bed Rear Boundary	6.4 mm	0.0 mm
Bed Forward Boundary	553 mm	807 mm
Primer Input:		
Length	51mm	51mm
Flow Rate	.27 kg/mm/sec	.05 kg/mm/sec

Table III. Propellant Combustion Parameters

	155mm Howitzer	5/54 Gun	
Activation Energy (KJ/mol)	62.8	62.8	
Pre-exponential (cm/sec)	2.43×10^5	7.07×10^4	
Reference Surf Temp (K)	623	650	
Thermal Conductivity ($J/cm^2/secK$)	8.73×10^{-4}	8.73×10^{-4}	
Thermal Diffusivity (cm^2/sec)	8.68×10^{-4}	8.68×10^{-4}	
Ignition Temperature (K)	450	428	
Temperature Sensitivity (/K)	0.0054	0.0045	
Steady State Burning Rate			
Coefficient $cm/s(MPa)^n$	0.387	0.0598	a
Exponent	0.7	1.2294	a
		0.597	b
		0.4194	b
		0.178	c
		0.7965	c

a - $P < 17.2$ MPa

b - $17.2 < P < 37.9$ MPa

c - $37.9 < P < 690$ MPa

V. 155mm HOWITZER

The standard 155mm howitzer charge was made into a full bore bag, an experimental charge to approach one dimensional geometry. No free space exists between bag and chamber wall. For the given propellant weight, the charge was shorter (55cm) than the standard bag charge (76cm). The only other change from the standard charge was the removal of the center core igniter to permit only base ignition.

Earlier NOVA calculations of the 155 simulated the gun pressure wave behavior when a constant was added to the quasi-steady regression rate (as it was in a similar 5/54 gm calculation[2]). A constant 0.5 cm/sec gave an acceptable match with a typical experimental record. At low pressure (less than 5 MPa) the regression rate then exceeded four times the quasi-steady rate. At pressures above 50 MPa, the multiple was less than 1.5 which is smaller but still not insignificant. The effects of the increase are felt in the first cycle of the wave; damping thereafter is qualitatively the same as in the quasi-steady rate case.

Later examination of the additive constant simulations showed that adjustment of the bore resistance and projectile seating distance were also sufficient for an adequate simulation. Projectile seating distance is a measurable input and should not be an arbitrary variable. It was unfortunate that it was incorrectly stated in some simulations. What resulted was the finding that it could act as an adjustable constant. An additive burning rate constant had a smaller effect on the pressure wave amplitudes. Figure 1 shows the simulations for the revised input data [curve labeled (QS)]. Shaded portion shows test results. Amplitudes for the earlier version with an additive constant of 1.27 cm/sec were only marginally (10%) higher. An unpleasant conclusion drawn from this comparison is that either projectile motion or regression rate may be arbitrarily adjusted to force simulations to match test data.

Bore resistance is derived from Picatinny Arsenal data[13] for 155mm howitzer with charges zone 3 and 4. The data scatter, especially at low projectile velocities, causes a relatively wide interval for a resistance estimate. The actual values used in a linear interpolation are as follows:

Distance Traveled (cm)	0	1.5	9.1	514
Resistance Pressure (MPa)	6.9	41.4	17.2	10.3

The principal effect of the transient regression was to increase the amplitude of pressure wave beyond the already too high predictions with the quasi-steady regression. Figure 1 compares predictions with experiment (two tests). Flame speed of about 0.4mm/μs was unaffected (Figure 2).

One variation changed the quasi-steady burning rate dependence by increasing the pressure exponent to 0.85 while retaining the same Arrhenius activation energy and reference surface temperature. Earlier calculations by Horst[14] in a 5 inch gun predicted a lower amplitude with higher exponent because the effect is to depress the low pressure regression rates and to increase the burning rate at pressures above that where the rate is unchanged, usually called the pivot pressure. (With this propellant, the burning rate at 7MPa drops from 1.5 cm/sec to .72 cm/sec.) Pressure wave amplitudes decreased as seen in Figure 1.

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13. *J. DeLorenzo and A. C. Vallado, "Compilation of Traces and Tabulation of Round-to-Round Data for the 155mm XM211 Program (Phase I) Conducted at Picatinny Arsenal 12-13 April 1976, unpublished, Picatinny Arsenal, May 1976.*

14. *A. W. Horst, "Influence of Propellant Burning Rate Representation on Gun Environment Flamespread and Pressure Wave Predictions", IHMR 76-255, March 1976.*

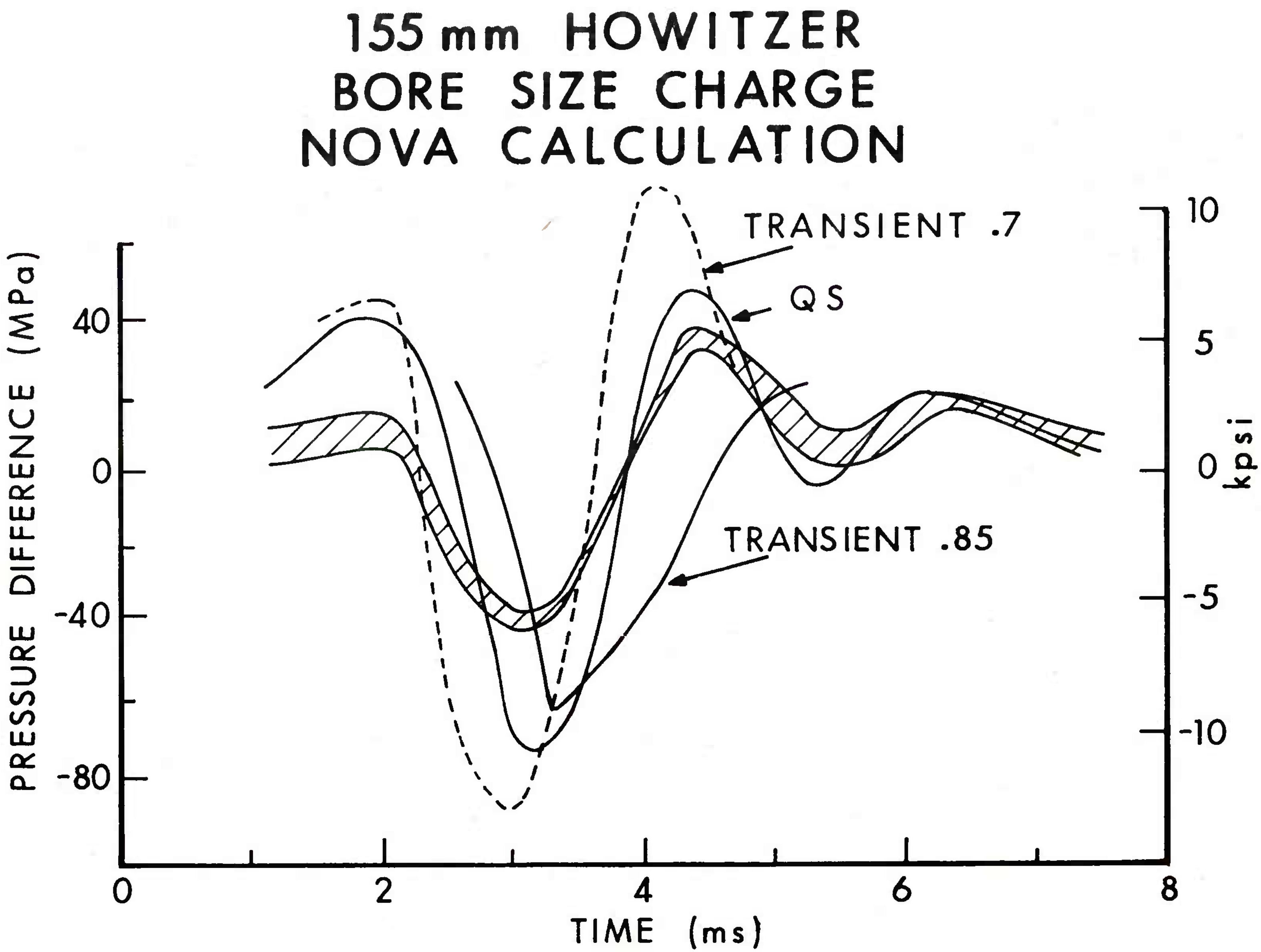

Figure 1. Pressure Wave Predictions for 155mm Howitzer

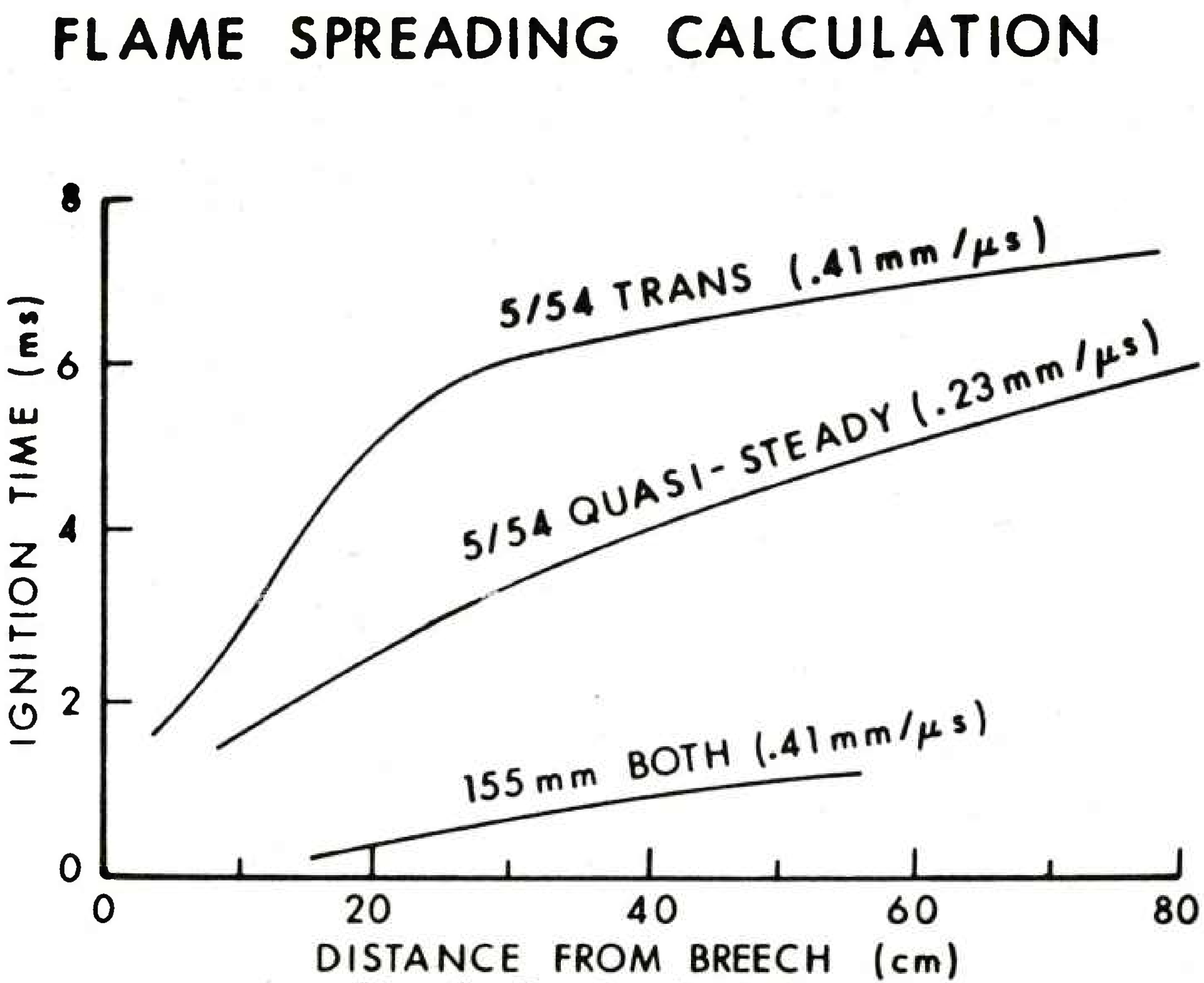

Figure 2. Flame Spreading Predictions

VI. 5/54 GUN

The standard Navy 5/54 propelling charge and projectile were modified by (1) replacing the packing elements between charge and projectile by an incompressible plastic disc to eliminate effects of compressible packing and (2) replacing the metallic rotating band with a plastic band to eliminate almost all rotating band resistance to motion. Two igniter configurations were fired: the standard bayonet igniter, and a black powder base bad igniter.

(A note on nomenclature. "Igniter" here refers to the black powder or other material which provides the hot gases to ignite the propellant grains. There is a difference in Army and Navy use of "primer" and "igniter".)

Earlier calculations of the base pad igniter with an additive burning constant of 1.27 cm/sec, successfully simulated the test behavior (2).

It should be noted here that the transient burning model used in the 5/54 calculations differed from that in the 155 calculations in that there is no transition to a self-sustaining flame. Convective heat transfer from the chamber gases to the propellant surface is assumed to continue through the propellant flame. This heat is added to the flame heat feedback as computed by the Zeldovich model. Regression rates are thus higher than the quasi-steady rates even when any pressure transients end. This treatment gives a limiting analysis to show the worst case of combined transient and erosive burning.

Although it avoids an arbitrary decision on flame development, the results show it to be "too worst" to the extent that credible flow calculations are not obtained. The calculated pressure waves exceed the code's built-in limitations and thus the calculations stop on steep pressure transients during bed stagnation at the projectile base. Figure 3 shows the wave development for both igniters.

Explanation can be found in the relative regression rates of Figure 4. For the 155 howitzer the relative rate peaks around two and decays to the quasi-steady rate (relative rate 1.0). For the base ignited 5/54 gun, the relative rate rises to around five and then oscillates as it decays toward the quasi-steady rate. This oscillation correlates directly with the parameter $|u-u_p|$ which says that the convection from the chamber gas strongly contributes to the heat feedback to the propellant surface. Such an overstated regression rate creates a stronger pressure front which compacts the grains harder against the projectile base.

The effect on the flame spreading can be seen in Figure 2. The quasi-steady regression and the cubic profile method for heating to ignition combine for a flame spreading rate of around 0.25mm/μs, not far from the sound speed in the undisturbed gas. The fully transient solution produces a slow initial spreading (.04mm/μs) at the breech end

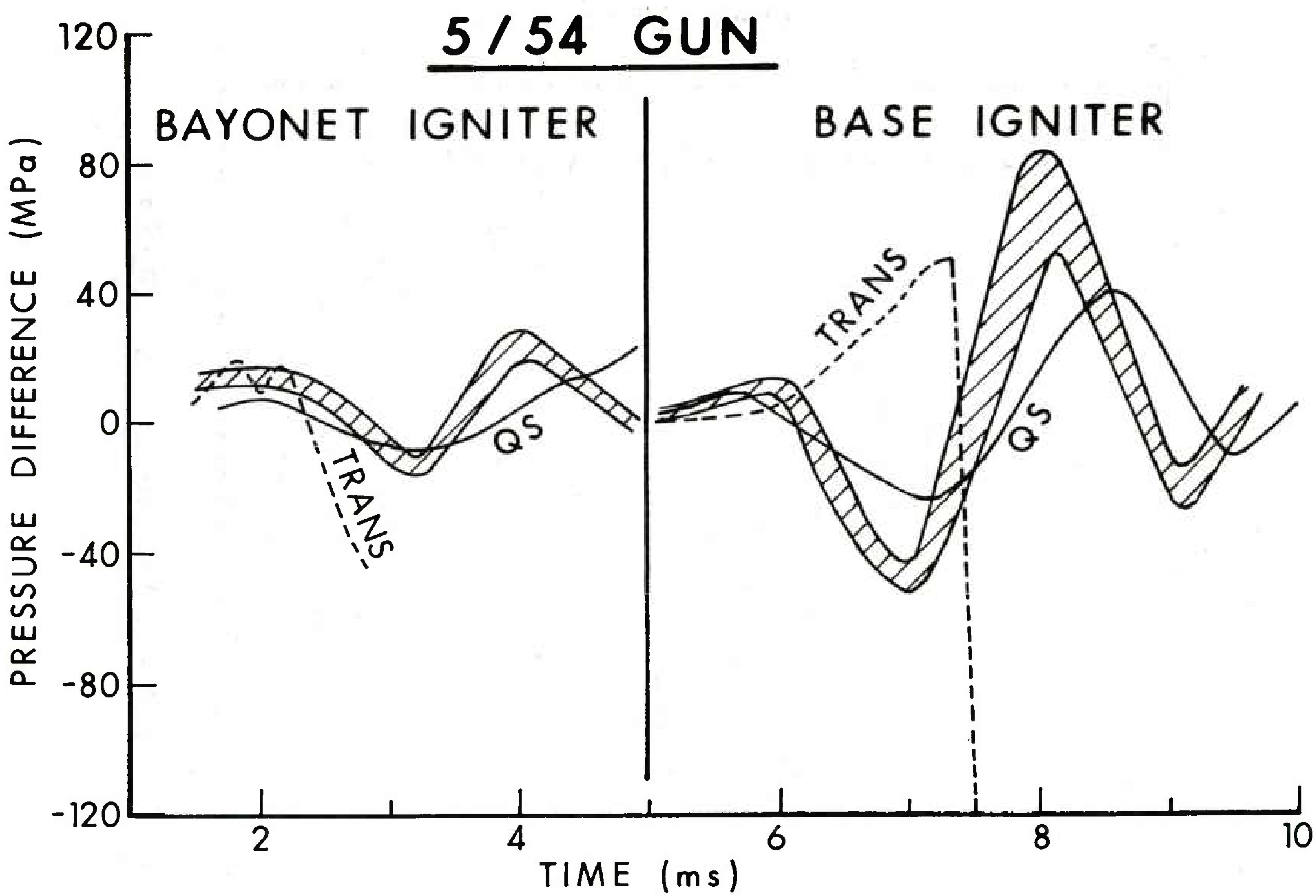

Figure 3. Pressure Differences for 5/54 Gun

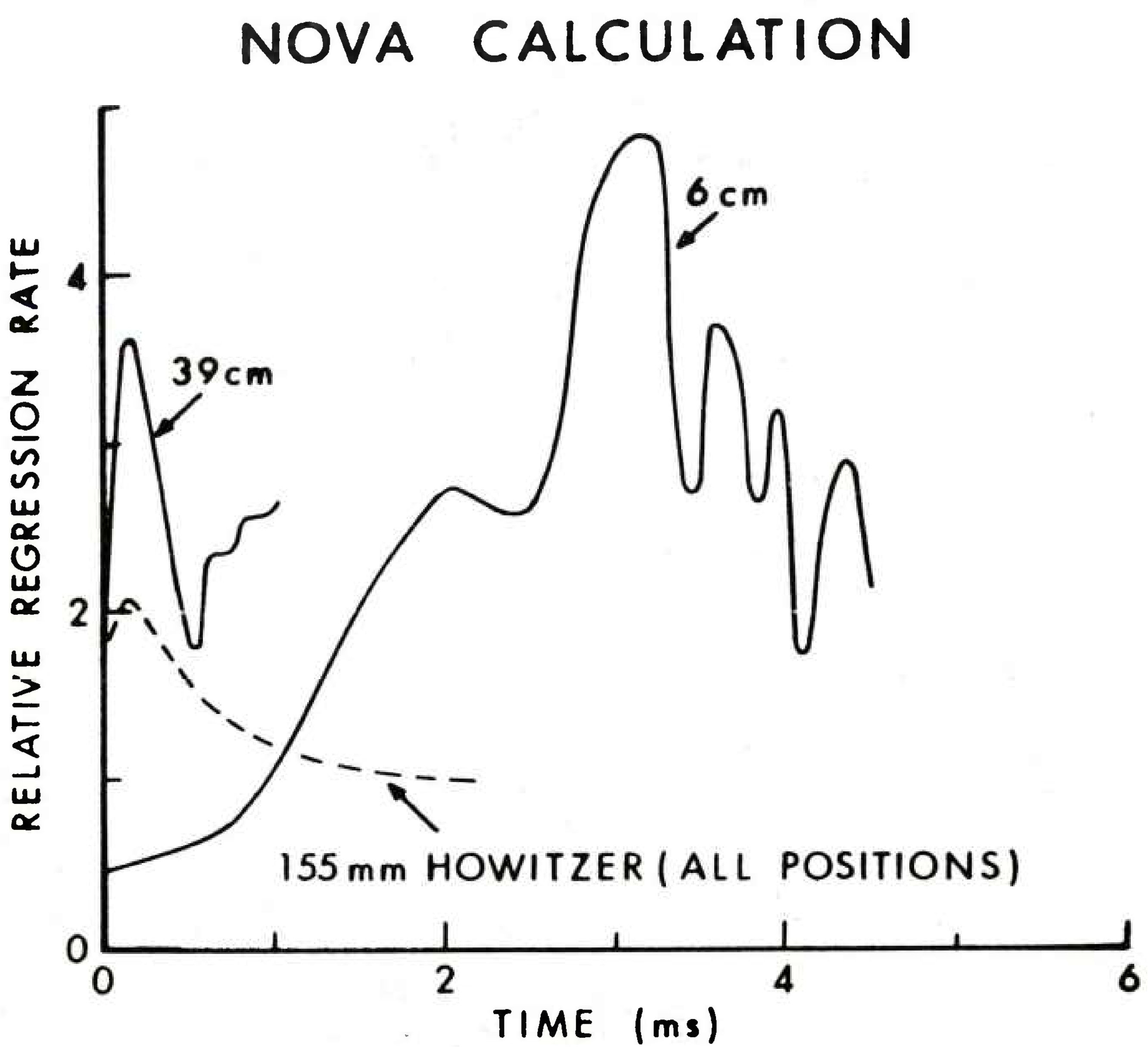

Figure 4. Relative Regression Rates

accelerating to 0.4 mm/μs at the forward end. The cause for the difference is not clear. A major difference between the two guns is that the 5/54 has a lower igniter input rate. How this fact couples with the heat conduction solution remains to be determined. A summary of effects for both guns can be seen in Table IV.

Table IV. Summary of Results

Case	Burning Rate	Igniter	Flame Speed (mm/μs)	ΔP* (MPa)	P_{max}(MPa)
			155mm Howitzer		
1	Steady	Base	0.4	-73/39	293
1T	Transient	Base	0.4	-90/76	NC
2	Add 0.5 cm/s	Base	0.4-0.5	-83/56	308
Experimental		Base	Unknown	-40/35	235
3	n = 0.85	Base	0.3	-50/NC	NC
			5/54 Gun		
11	Steady	Base	0.1-0.25	-24/40	235
11T	Transient	Base	0.04-.4	NC	NC
12	Steady	Bayonet(22")	0.4	-8/17	241
12T	Transient	Bayonet (22")	0.4	NC	NC

* Breech Pressure - Forward Pressure. First number is maximum first negative difference; second number is maximum second positive difference.

The bayonet primer configuration exhibits no such differences. As seen in Figure 5, the rates are all about the same and equal to the rate measured by McClure and East[15] with M26 propellant. (Such agreement may be fortuitous given the differences in grain sizes and composition).

VII. THE CONVERGENCE BARRIER

The non-linear equation and boundary condition require an iteration to obtain a consistent set for burning rate, surface temperature, and heat flux. Kooker and Nelson used a convergence criterion of about 10^{-6}K

15. *D. R. McClure and J. L. East, "Experimental Techniques for Investigating the Start-Up Ignition/Combustion Transients in Full Scale Charge Assemblies", 11th JANNAF Combustion Meeting, Pasadena, CA, September 1974.*

for surface temperature and 10^{-7} cm/sec for burning rate. Later study showed that relaxing these by two orders of magnitude caused a 10% change in peak relative burning rate but, more usefully, only a 1% error in gas generation during the transient. The earlier Zeldovich study by Caveny et al[4] used an explicit scheme without iteration by using the last computed value for the regression rate.

At first, the convergence criteria were set at 10^{-4} percent of regression rate and surface temperature. These translate to about 10^{-3}K and 10^{-5} cm/sec during the transients. It was soon discovered that convergence was not obtained in ten iterations when the regression rate exceeded about 3 cm/sec.

Because it was too costly to decrease the problem time step to accommodate the regression transient, an operator splitting technique was adopted[16] as had been previously used by Dwyer[17]. Each hydrodynamic time step is split into the necessary sub-steps to retain convergence of the regression rate solution with a MacCormack scheme L_f for the hydrodynamics and a Gear Scheme L_c for the chemistry, Dwyer[17] applied the operators in a sequence

$$u_i^{n+2} = L_f L_c L_c L_f u_i^n . \tag{13}$$

to advance the dependent variable u two time steps. This present study used the simple scheme

$$u_i^{n+1} = L_f L_c u_i^n , \tag{14}$$

which is a crude approximation of a scheme originally intended for multidimensional problems. Some improvement can be made by interpolating the pressure field across the interval for each time sub-step. Other users have assigned a single representative value of the hydrodynamic variables for all the sub-steps. The Navy gun calculations used the interpolated values; the Army calculations used only the forward value. Sensitivity to the use of either values has yet to be determined.

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16. *N. N. Yanenko, The Method of Fractional Steps, translated by M. Holt, Springer-Verlag, Berlin, 1971.*

17. *H. A. Dwyer and B. R. Sanders, "Modeling of Unsteady Combustion Phenomena", AIAA Paper 77-136, 15th Aerospace Sciences Meeting, January 1977.*

Even the time-splitting technique was inadequate for the task when the regression rate exceeded about 10 cm/sec. The same trouble was noted by Kooker and Nelson in that the time step had to be cut to about 10^{-8} sec when the rate was about 6 cm/sec. It is clear that some drastic changes are needed if accurate and affordable calculations of the transient rate are to be made at high regression rates. For the present problem, the convergence failure occurs as the compression wave strikes the projectile base and the pressure nears 150 MPa where the quasi-steady regression rate is about 12 cm/sec and the transient rate about 13 cm/sec. There a time step of 10^{-7} sec is too large.

There can be no temporary acceptance of the small time step at the local high pressure region because the whole bed will soon exceed 200 MPa. A compromise can recognize that for quasi-steady regression rates above 10 cm/sec, the transients may be ignored. Previous studies[18] predicted that the transient rate approaches the quasi-steady rate for pressures above about 50 MPa.

Thus, those transient calculations which go to completion have had the transient combustion terminated whenever the quasi-steady regression rate exceeded 10 cm/sec. If a transient still exists at that pressure (or will be later created by the passage of a steep compression wave through the bed) an error is thereby introduced. For now it is assumed that the error can be neglected.

A new iteration algorithm is needed before fully transient calculations can be completed.

VIII. CONCLUSIONS

1. Transient burning can affect interior ballistics calculations.

2. Zeldovich model response agrees with uncoupled response in similar pressure history.

3. For practical IB calculations, cubic profile may be unsatisfactory for flame spreading with weak igniters.

4. Further evaluation awaits improvements in convergence and transition to self-sustaining combustion.

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18. *C. W. Nelson, "Response of Three Types of Transient Combustion Models to Gun Pressurization", BRL Memorandum Report No. 2752, May 1977, AD #A041079.*

REFERENCES

1. E. B. Fisher and A. P. Trippe, "Application of a Flame Spread Model to Design Problems in the 155mm Propelling Charge", Proceedings of the 12th JANNAF Combustion Meeting, Newport, RI, August 1975.

2. A. W. Horst, C. W. Nelson, and I. W. May, "Flame Spreading in Granular Propellant Beds: A Diagnostic Comparison of Theory to Experiment", AIAA Paper 77-856, 13th AIAA Propulsion Specialists Meeting, Orlando, FL, July 1977.

3. D. E. Kooker and C. W. Nelson, "Numerical Solution of Three Solid Propellant Combustion Models During a Gun Pressure Transient", Proceedings of the 12th JANNAF Combustion Meeting, Newport, RI, August 1975.

4. L. H. Caveny, M. Summerfield, and C. W. Nelson, "Ignition Transients and Pressurization in Closed Chambers", Proceedings of the 11th JANNAF Combustion Meeting, Pasadena, CA, September 1974.

5. P. S. Gough, "A Quasi-One-Dimensional Two Phase Flow Model of Interior Ballistics: Towards a Universal Gun Code", Proceedings of the 13th JANNAF Combustion Meeting, Monterey, CA, September 1976.

6. P. S. Gough, "Numerical Analysis of a Two-Phase Flow with Explicit Internal Boundaries", Paul Gough Associates Report PGA-TR-76-2, September 1976 (See also NOS Indian Head Report IHCR 77-5, April 1977).

7. T. J. Ohlemiller, L. H. Caveny, L. DeLuca, and M. Summerfield, "Dynamic Effects on Ignitability Limits of Solid Propellants Subjected to Radiative Heating", Fourteenth Symposium (International) on Combustion, The Combustion Institute, pp. 1297-1307, (1973).

8. L. DeLuca, T. J. Ohlemiller, L. H. Caveny, and M. Summerfield, "Radiative Ignition of Double Base Propellants: II Pre-Ignition Events and Source Effects", AIAAJ, 14 (8), p. 1111-1117 (1976).

9. W. H. Andersen, "Model of Transient Ignition to Self-Sustaining Combustion", Comb. Sci. and Tech., 5, p. 75, 1972.

10. K. K. Kuo, R. Vichnevetsky and M. Summerfield, "Theory of Flame Front Propagation in Porous Propellant Charges under Confinement", Princeton Univ. AMSE Report 1000, August 1971 (AD #762063).

11. D. E. Kooker, "Numerical Predictions of Ignition and Flamespreading in Ozone/Oxygen Mixture", Proceedings of the 14th JANNAF Combustion Meeting, Colorado Springs, CO, August 1977.

12. C. W. Nelson, "Comparison of Predictions of Three Two-Phase Flow Codes", 13th JANNAF Combustion Meeting, Monterey, CA, September 1976.

13. J. DeLorenzo and A. C. Vallado, "Compilation of Traces and Tabulation of Round-to-Round Data for the 155mm XM211 Program (Phase I) Conducted at Picatinny Arsenal 12-13 April 1976, unpublished, Picatinny Arsenal, May 1976.

14. A. W. Horst, "Influence of Propellant Burning Rate Representation on Gun Environment Flamespread and Pressure Wave Predictions", IHMR 76-255, March 1976.

15. D. R. McClure and J. L. East, "Experimental Techniques for Investigating the Start-Up Ignition/Combustion Transients in Full Scale Charge Assemblies", 11th JANNAF Combustion Meeting, Pasadena, CA, September 1974.

16. N. N. Yanenko, The Method of Fractional Steps, translated by M. Holt, Springer-Verlag, Berlin, 1971.

17. H. A. Dwyer and B. R. Sanders, "Modeling of Unsteady Combustion Phenomena", AIAA Paper 77-136, 15th Aerospace Sciences Meeting, January 1977.

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